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by

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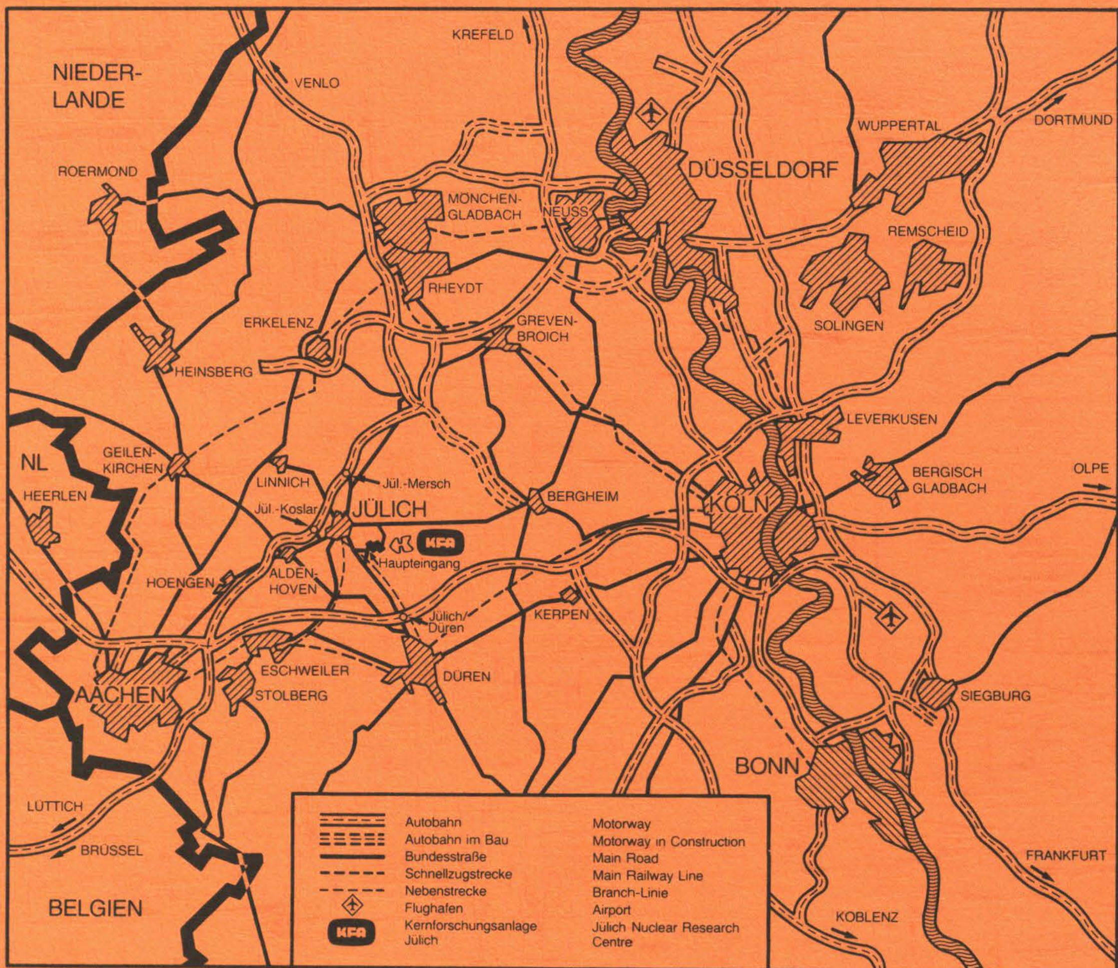

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An exploration of the interface domain between accelerators and fusion devices and their relation to the development of variable ion-to-neutron reactions for future nuclear energy systems

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Abstract

Some basic issues concerning accelerator initiated and fusion sustained nuclear energy systems are examined. For this purpose we identify selected nuclear fusion reactions characterized by a variable ion-to-neutron content and explore their intrinsic couplings and regenerative features. These are then related to particular systems concepts which emphasize fusion physics and accelerator technology.

It is concluded that several light-element reaction systems possess appealing and interesting properties and can further be associated with selected advanced nuclear technologies. Their eventual implementation as nuclear energy systems requires further research in fusion physics, accelerator technology and mathematical physics. Because of the substantial potential benefits of such nuclear energy systems, it is concluded that research in this area should be pursued with much vigour.

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I INTRODUCTION

The selective integration of complementary processes constitutes a basic feature of our physical world. It is particularly prevasive in biology, is recognized in many collective phenomena in physics, and is increasingly pursued as an operational practice in industry.

More recently it has been shown that synergetic considerations constitute an integrative characterization of nuclear energy technologies and may be used as a framework to aid in the more effective pursuit of emerging research developmental strategies of the "Second Generation of Nuclear Engineering". The distinguishing feature here involves the judicious integration of fission, fusion and accelerator induced phenomena and their associated technologies, Fig. 1.

While the scientific-technical features of the acceleration-fission and the fission-fusion interface is generally well identified and partially duplicative, Fig. 2, the acceleration-fusion interface seems - in general - less clear. It is our contention, however, that this latter domain is particularly worthy of pursuit because it possesses the potential of introducing systems operational features not possible otherwise. Among these we suggest the following:

1. Prospects for the enhanced use of charged particles in the nuclear reactions.
2. Possible establishment of charged particle reaction couplings and charged particle chains.
3. Attainment of a variable ion-to-neutron ratio and the introduction of selected advanced fusion fuel cycles.

The incorporation of these considerations in an acceleration-fusion nuclear energy systems context would lead to the following:

1. A reduced neutron content in the nuclear reaction will evidently provide for a consequent reduction of induced radioactivity and hence permit the introduction of radiologically "cleaner" forms of nuclear energy;

2. An enhanced charged particle content in the nuclear reaction will render efficient direct energy conversion feasible thus avoiding the common though less efficient thermal energy conversion cycle.

These considerations imply that the acceleration-fusion interface can differ in its functional effects in a most profound way in comparison to the acceleration-fission and fission-fusion interface domain. This distinction is suggested in Fig. 3 where we show the potential attainment of nuclear energy systems prospects essentially independent of the dominance of neutron catalysis; that is, the acceleration-fusion interface possesses the potential of approaching a "neutron-free" nuclear energy prospect.

It is our intent to provide a scientific-phenomenological and reaction-based delineation of the acceleration-fusion interface domain. Although we will take care to note experimental evidence of the physical attainability of the essential processes of relevance here, we do emphasize that considerable extensions of our understanding of selected basic nuclear and electrodynamic processes must still be sought and specialized technological developments need to be undertaken.

II PHYSICAL-TECHNICAL CONTEXT

The essential and necessary features of a broadly based scientific-technical enterprise must possess both a physical basis and a systems context. Both of these features can be identified for the domain of interest here.

II.1 Accelerators and Fusion Devices

A commonly held view is that accelerators and fusion facilities are unrelated devices with little prospect for a useful future symbiosis. This view has in recent years been shown to be quite unfounded and is best illustrated in the following listing.

a) Neutral Beam Injectors

Most current magnetic confinement devices have recently become equipped with accelerators which inject low energy neutral particles into the plasma. The purpose is to provide plasma heating although their use for fueling purposes and spatial ion control is also envisaged.

b) Ion Beam Fusion

Research in inertial confinement pellet fusion is now being pursued with various types of accelerators and various types of light and heavy ions. It is anticipated that the superior localization of energy with ions will overcome the inefficient energy-pellet coupling experienced with laser fusion. (We interject here that laser-based ICF also represents a form of acceleration-fusion symbiosis since particle accelerators and electromagnetic-wave generators can be viewed as generically equivalent.)

c) Impact Fusion

A recent technological acceleration-fusion development involves the use of ultra-high speed electromagnetic rail guns which accelerate macroparticles for impact on a suitable stationary target. The macroparticles may be of mass up to a gram and its required speeds are of the order of 1000 km/s.

d) Colliding Beam Fusion

Fusion reactions involving oppositely directed ion beams have been observed at intersecting-ring accelerator installations. The dominance of Coulomb scattering and the consequent out-scatter loss of the ions has rendered this approach energetically unfavourable. Magnetically redirecting such scattered particles back into a high particle density appears promising.

e) Muon Catalyzed Fusion

In this concept, a high energy proton accelerator is used to generate subatomic particles called muons. These muons possess one electronic charge with a mass 207 as heavy as an electron. Thus, they can enter into a very tight Bohr orbit of a hydrogen isotope allowing it therefore to approach another hydrogen isotope sufficiently closely to significantly increase the probability of fusion. The significant distinction here is that fusion reaction can occur at almost room temperature justifying its label of "Cold Fusion" (10^2-10^3 K) in relation to conventional MCF "Hot Fusion" (10^7-10^8 K).

II.2 Fusion Reaction Characterization

The total rate of nuclear energy release in a multi-species fusioning domain is given by

$$P = \sum_i \sum_j R_{ij} \quad Q_{ij} \tag{1}$$

where i and j refer to the interacting fusing particles, R_{ij} is the total reaction rate (s^{-1}) and Q_{ij} is the average nuclear energy released per reaction (MeV). Power is here therefore expressed in units of MeV/s and can be converted as needed.

The reaction density rate, r_{ij}, possessing units of $cm^{-3}s^{-1}$ is related to R_{ij} via

$$R_{ij} = \int_V r_{ij}(\underline{x}) \; dV = r_{ij} V \tag{2}$$

with V representing the reaction volume and $\underline{x}$ the position coordinate. This reaction rate is defined in terms of the primary parameters and function as follows:

$$r_{ij} = \int_{\underline{v}_i} \int_{\underline{v}_j} \sigma_{ij}(v_{rel}) \; v_{rel} \; \frac{N_i N_j}{1+\delta_{ij}} \; f_i(\underline{v}_i) \; f_j(\underline{v}_j) \; d\underline{v}_i \; d\underline{v}_j$$

$$= \frac{N_i N_j}{1+\delta_{ij}} \int_{\underline{v}_i} \int_{\underline{v}_j} \sigma_{ij}(v_{rel}) \; v_{rel} \; f_i(\underline{v}_i) \; f_j(\underline{v}_j) \; d\underline{v}_i \; d\underline{v}_j \tag{3}$$

Here, N_i and N_j are the densities of the reacting particles each characterized by a normalized density distribution function $f_i(v_i)$ and $f_j(v_j)$ in velocity phase-space; the relative velocity is formally defined by

$$v_{rel} = |\underline{v}_i - \underline{v}_j| \tag{4}$$

and $\sigma_{ij}(v_{rel})$ is the associated microscopic fusion cross section; finally, the Kronecker delta δ_{ij} is inserted to allow for the possibility of fusion among identical particles.

The above illustrates the important parameters in a fusion energy context: (1) the number of distinct reactions r_{ij}, (2) the particle densities N_i and N_j, (3) their energy-velocity distributions together with their relative direction of motion, and (4) the associated cross sections.

Convention has assigned specific forms of expression for r_{ij}. If the distributions are known or assumed - such as the Maxwellian distributions - then one writes

$$r_{ij} = \frac{N_i N_j}{1+\delta_{ij}} \iint \sigma_{ij} \, v_{rel} \, M_i(\underline{v}_i) \, M_j(\underline{v}_j) \, d\underline{v}_i \, d\underline{v}_j$$

$$= \frac{N_i N_j}{1+\delta_{ij}} \, \langle \sigma v \rangle_{ij} \tag{5}$$

For the case of nearly monoenergetic and monodirectional processes - such as those involving ion beams - one obtains

$$r_{ij} = \frac{N_i N_j}{1+\delta_{ij}} \iint \sigma_{ij} \, v_{rel} \, f_i(\underline{v}_i) \, \delta(\underline{v}_i - \underline{v}_{ij}) \, f_j(\underline{v}_j) \, \delta(\underline{v}_j - \underline{v}_{jo}) \, d\underline{v}_i \, d\underline{v}_j$$

$$= \frac{N_i N_j}{1+\delta_{ij}} \, \sigma_{ij}(v_o) \, v_{o,ij} \tag{6}$$

Finally, for the case that nuclear catalytic processes are involved, the cross section takes on an entirely different physical meaning - based on tunneling processes rather than direct collisional effects - and one writes

$$r_{ij} = \frac{N_i N_j}{1+\delta_{ij}} \{\cdot\cdot\}$$

$$= \frac{N_i N_j}{1+\delta_{ij}} K_{ij} = \lambda_{ij} N_j \tag{7}$$

We re-emphasize that N_i and N_j are not simply restricted to the densities of tritium and deuterium as envisaged for the first generation of fusion reactors. Allowing for fusion mechanism of confinement, directed-beams, and nuclear catalysis suggests access to a considerably expanded set of fusion reaction as we indicate next.

II.3 Expanded Set of Fusion Reactions

It is common to list simply the $D+T \rightarrow n+\alpha$ fusion reaction because it appears to be the most easily attainable. However, there exist numerous light element exoergic reactions accessible by specialized means to be discussed subsequently. For now we list some of these reactions, their reaction Q-value, and their associated ion-to-neutron ratio, Table I.

The important feature of the listings in Table I is that neutron production appears less frequently than charged particle production; indeed, the Helium-3 and proton-based reactions are essentially neutron-free. As suggested in the introduction, the choice of fusion reaction must therefore be determined by other factors including the extent to which neutrons might be deliberately produced, perhaps just enough to provide for an adequate energy balance via fissile fuel breeding with this fusion neutron. Note that this energy use of the fusion neutron provides close to 200 MeV of thermal energy to the overall system energy budget and is a factor of 10 or more greater than the associated fusion Q-value.

Two additional issues need to be addressed: one is whether additional reaction phenomena appear and two, the technical attainment of these reactions. We address these issues next.

III REACTION SYNERGISM

The conventional approach in nuclear energy systems analysis is to identify the one dominant exoergic reaction and then to optimize a design for its exploitation. We find here that the suitable integration of a system of reactions is necessary and can be well utilized for reaction-sustainment purposes.

III.1 Fusion Reaction Coupling

The process of fusion reaction coupling is readily illustrated in terms of the elementary reactions #1 and #2 of Table I. We take the two-channel reaction #2

$$D+D \begin{array}{l} \nearrow \; T+p \\ \\ \searrow \; {}^3He+n \end{array} \tag{8}$$

which is known to occur with almost identical probability. As indicated in Fig. 4, for the range of most common current interest, D+T fusion occurs even more likely than D+D so that the tritium bred in Eq. (8) may fuse with the background host deuterium. We represent these concurrent reactions by

$$\begin{array}{lcl} R_{DD,1} & : & D+D\rightarrow T+p \\ & & \quad\;\; \swarrow \\ R_{DT} & : & D+T\rightarrow n+\alpha \\ \\ R_{DD,2} & : & D+D\rightarrow {}^3He+n \end{array} \tag{9}$$

Here $R_{ij,k}$ refers to the associated fusion reaction rate of species i and j and k identifies the appropriate channel, if any. Since, evidently

$$R_{DD,1} = R_{DD,2} \tag{10}$$

and if temperature/plasma conditions are right so that the bred tritium is consumed at its rate of production, then

$$R_{DD,1} = R_{DT} \tag{11}$$

and we write the above system as

$$5\ D \rightarrow {}^3He+p+\alpha+2n\ ;\ Q = 24.9\ ;\ i/n = 3/2 \tag{12}$$

However, Eq. (11) also leads to an important constraint on the tritium and deuterium densities. In view of Eq. (5) and for the system described by this equation, we get

$$\frac{N_D^2}{2} <\sigma v>_{DD,1} = N_D N_T <\sigma v> \tag{13}$$

and hence the ratio of tritium-to-deuterium density is given by

$$\begin{aligned}\frac{N_T}{N_D} &= \frac{1}{2}\,\frac{<\sigma v>_{DD,1}}{<\sigma v>_{DT}} \\ &= \frac{1}{4}\,\frac{<\sigma v>_{DD}}{<\sigma v>_{DT}}\end{aligned} \tag{14}$$

For a magnetically confined system, this ratio can vary by several orders of magnitude and will evidently require good ion control.

An extension of Eq. (9) is readily established by considering the case of burning the ^3He at its rate of production as follows:

$$\begin{array}{lll} D+D & \rightarrow & T+p \\ D+T & \rightarrow & n+\alpha \\ D+D & \rightarrow & {}^3He+n \\ D+{}^3He & \rightarrow & \alpha+p \\ \hline 6\ D & \rightarrow & 2n+2\alpha+2p\ ;\ \ Q = 43.2\ ;\ \ i/n = 4/2 \end{array} \tag{15}$$

Here, 67 % of the reaction products are ions and, as can be shown, they carry 62 % of the total energy of the reaction system.

One can readily identify some additional splitting processes. Thus considering only the T-producing D+D reaction channel, conditions might exist such that the following holds:

$$\begin{array}{l} D+D \rightarrow T+p \\ D+T \rightarrow n+\alpha \\ \quad T+T \rightarrow \alpha+2n \end{array} \qquad (16)$$

Here, the channel ratios involving reaction products may play an important role.

As a final example of reaction coupling, we list one which displays all the features of a fusion chain. Consider the selective coupling of reaction #10 with #13, Table I, in the form

$$\begin{array}{l} p+{}^{6}Li \rightarrow {}^{3}He+\alpha \\ \quad {}^{6}Li+{}^{3}He \rightarrow p+2\alpha \end{array} \qquad (17)$$

Here ^{3}He acts as a chain link and the proton is the chain carrier. Whether or not a self-sustaining fusion chain can be established, either in the form of Eq. (17) or any other combination of reactions listed in Table I, needs further examination. We address some of the relevant questions next.

III.2 Fission Chain Reformulation

The concept of fusion chains may be well illustrated by analogy to the conventional fission chain phenomena. In its most elementary form we may write such a regenerative reaction chain as

$$n + Fi \rightarrow P_1 + P_2 + \nu n \qquad (18)$$

$$\underbrace{1n}_{\text{chain sustainment}} \qquad \underbrace{(\nu - 1)n}_{\text{parasitic neutron losses}}$$

where Fi is a fissile nucleus of the background fuel, P_1 and P_2 are two representative fission products, and ν represents the average number of neutrons released per fission event.

A more general fission chain process which includes neutron capture in the fuel as well as some neutron regeneration in parasitic neutron capture may be written as

$$n + Fi \longrightarrow \begin{cases} C + \gamma \\ P_1 + P_2 + \eta n \end{cases} \qquad (19)$$

$$\eta n \rightarrow \text{losses}$$

$$X + n \qquad Y + xn$$

Here C is the (n + Fi) capture product nucleus, η is the average number of neutrons released per neutron absorbed in a fissile nucleus, X is a suitable neutron multiplier which introduce a reduced neutron multiplication capability and Y is a reaction product.

The kinetic properties of the above - or any other - fission chain are determined by the time variation of the neutron population density N_n as determined by the mass-balance rate equation

$$\frac{dN_n}{dt} = \begin{Bmatrix} \text{neutron} \\ \text{production rate} \end{Bmatrix} - \begin{Bmatrix} \text{neutron destruction +} \\ \text{removal rate} \end{Bmatrix} \qquad (20)$$

This equation can take various forms depending upon the processes incorporated and the density phase-space characterization imposed. In general, the contributive terms to the right-hand part of Eq. (20) are terms which are either proportional to the neutron density N_n or independent of the neutron density.

Hence, we write

$$\frac{dN_n}{dt} = a_0 + a_1 N_n \qquad (21)$$

with a_i as the appropriate functions or constants. Under some functional and/or physical restrictions, a normalization may be imposed and we write

$$\frac{dN_n}{dt} = a^* N_n \qquad (22)$$

with a* as the fission kinetics bifurcation parameter. Thus, upon integration, we find that the kinetics of the fission chain phenomena are determined by

$$a^* = \begin{cases} > 0 \text{ , supercritical} \\ = 0 \text{ , critical (steady-state)} \\ < 0 \text{ , subcritical} \end{cases} \qquad (23)$$

With the fission-chain characterization thus formulated, we consider, in an analogous vein, the concept of fusion chains.

III.3 Fusion Chains

We had suggested, Eq. (17), that the fusion reaction system

$$\begin{aligned} &p + {}^{6}Li \rightarrow {}^{3}He + \alpha \\ &\quad {}^{6}Li + {}^{3}He \rightarrow p + 2\alpha \end{aligned} \tag{24}$$

constitutes a chain. However, reference to reaction #10, Table I, makes it clear that the two-channel reaction scheme of the ${}^{6}Li + {}^{3}He$ fusion process will prevent the establishment of a closed sustainable fusion chain. Some thought suggests that the high energy alpha particle in the ${}^{6}Li + {}^{3}He$ can be used to breed concurrently another proton as follows:

$$\begin{aligned} &p + {}^{6}Li \rightarrow {}^{3}He + \alpha \\ &\quad {}^{6}Li + {}^{3}He \rightarrow \begin{cases} {}^{7}Be + D \\ p + \alpha + \alpha \end{cases} \\ &\quad {}^{6}Li + \alpha \rightarrow p + {}^{9}Be \end{aligned} \tag{25}$$

Note that, here, the ${}^{3}He$ and the fast alpha particle product are chain links and the proton is the chain carrier.

For reasons of additional clarification, we list two more sample fusion chains in Fig. 5. Note that the fusion chain system of Eq. (25), as well as those of Fig. 5 are largely neutron-free and hence radiologically relatively "clean".

It now becomes evident that the kinetics analysis of fusion chains should be a priority consideration. In particular, the question of the existance or non-existance of fusion-chain excursions needs to be addressed.

The paucity of certain fusion cross sections and channel ratios, together with the slowing down characteristics of some of the ions - as well as system operational features and ion leakage - argue that a detailed and precise kinetics analysis of a particular fusion chain phenoma may be premature. However, a general and non-specific analysis can be undertaken as follows.

Consider the symbol C representing a chain carrier of a general fusion chain. Then, it follows that the mass-balance rate equation for the density of this chain carrier, N_c, is given by

$$\frac{dN_c}{dt} = \left\{ \begin{matrix} \text{production} \\ \text{rate of c} \end{matrix} \right\} - \left\{ \begin{matrix} \text{destruction+removal} \\ \text{rate of c} \end{matrix} \right\} \qquad (26)$$

In view of the fission-chain discussion and the above fusion-chain formulation, we identify the following classes of processes which affect the density of the chain carrier N_c:

1) There may be several distinct production, destruction, and removal processes which are directly proportional to N_c;

2) There may exist some processes - e.g. external subsidization, etc. - which contribute to N_c and which are essentially independent of N_c and therefore constitute constants;

3) Finally, many chain carriers may fuse among themselves (e.g. D + D, T + T, $^3He + ^3He$, ...) and hence these reaction rates are proportional to N_c^2 (see Eq. (5) for i = j).

We conclude therefore, that in general, the fusion chain kinetics are defined by

$$\frac{dN_c}{dt} = a_0 + a_1 N_c - a_2 N_c^2 \tag{27}$$

where the coefficient function a_0, a_1, and a_2 span the domain

$$a_0 \gtrless 0 \tag{28a}$$

$$a_1 \gtrless 0 \tag{28b}$$

$$a_2 > 0 \tag{28c}$$

Equation (27) is known as Ricatti's equation for which some relevant analytical solutions can be identified. We indicate in Fig. 6 for the case of constants a_0, a_1, and a_2, under which a supercritical fusion chain might result.

Two points seem paramount in this discussion of fusion supercriticality. First, unlike a fission chain, the fusion reaction growth mode is bounded, but the magnitude of this asymptote above the initial conditions as well as the time involved in approaching this chain carrier plateau needs further research. Second, this fusion excursion phenomena may be profitably exploited for energetic purposes since it might be sustained as a controlled and intrinsic phenomena in support of energy multiplication.

IV SYSTEMS PERSPECTIVE

The preceding discussion suggests that either considerable extensions of existing fusion/acceleration systems or the development of special purpose systems need to be established before these variable ion-to-neutron reactions can be considered as attainable nuclear energy sources. We address ourselves to this issue here recognizing that three classes of approaches - confinement, directed beam, and nuclear catalysis - appear to be of interest.

IV.1 Confinement

The strategy to ionize, heat, confine a fusing substance constitutes the underlying basis of existing magnetic and inertial confinement approaches to fusion energy. In order to exploit the advanced fusion fuel cycles discussed here, one will need to operate at temperatures some two order of magnitude higher than currently available, Fig. 4, necessitating then also the development of efficient electromagnetic energy converters. These topics are largely within the existing bounds of current plasma physics research and hence will not be further discussed herein. Instead, we discuss next some fundamentally different approaches to fusion energy.

IV.2 Directed Beam

The classification "directed beam" refers to those systems in which a sufficiently high relative velocity between the fusing ion pairs is established with accelerators. Here one can identify three further subclassifications:

1. beam-target interaction,
2. colliding-beam interaction,
3. redirected-beam interaction.

The beam-target interaction approach, Fig. 7a, has failed as an energy-producing device because the Coulomb interaction either scatters the accelerated ion out of the interaction domain or causes sufficient energy loss so that fusion reactions become increasingly less likely.

Colliding-beam fusion involves two intersecting beams and is illustrated in Fig. 7b. While, as in the beam-target approach, there exists no difficulty in attaining a sufficiently high relative velocity of the ion pairs, the prevalence and effectiveness of the long-range Coulomb forces introduce an unacceptably large particle loss.

An attempt to reduce the adverse effects of ion outscattering, the redirected-beam interaction approach superimposes a magnetic field in the domain of interaction by a spatial distribution so as to redirect the scattered ions back into a high ion density domain. We suggest in Fig. 8 how this approach is attempted in the MIGMA systems concept. Thus, a relatively low energy accelerator injects ions tangentially into a domain between a suitably shaped magnetic field. The ion's initial motion combined with the Lorentz field force may lead to complex angular precessional particle trajectories which are expected to pass - even after scattering - through the central point at which the particle density is highest. The claim is that the adverse Coulomb scattering effects are thus minimized.

VI.3 Nuclear Catalysis

By "nuclear catalysis" we imply the existance of a nuclear particle with the property of neutralizing or reducing any forces which tend to oppose a fusion reaction. For example, if X were such a catalyst, then we could conceive of D + T fusion to be represented by, for example, the staged reaction sequence of

$$
\begin{aligned}
&T + X \rightarrow TX &&: \text{catalyzed atom formation} \\
&D + TX \rightarrow DTX &&: \text{catalyzed molecule formation} \\
&DTX \rightarrow n + \alpha + X &&: \text{fusion reaction}
\end{aligned}
\tag{29}
$$

which resembles a simple conventional chemical catalytic process. An alternative representation is

$$D + T + X \rightarrow DTX \rightarrow n + \alpha + X \tag{30}$$

which emphasise the repeated use of the nuclear catalyst X.

Of the many subnuclear particles available, it has been found that the negative mu-meson, μ^-, generally called a muon, appears to serve well for D + T fusion even at essentially room temperature.

Muons appear as a result of pion decay in almost any high energy reaction. The sequence typically involves a high energy proton, p, striking a nucleus Z,

$$p + Z \rightarrow \pi^- + \ldots \tag{31}$$

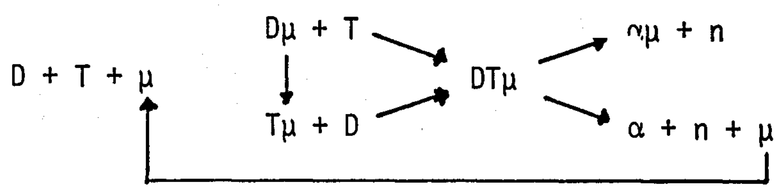
This pi-meson decays by the mode

$$\pi^- \rightarrow \mu^- + \ldots. \qquad \tau = 2 \times 10^{-8}\,\mathrm{s} \tag{32}$$

thus producing a muon, μ^-. This muon itself is radioactive and decays by

$$\mu^- \rightarrow e^- + \ldots. \qquad \tau = 2.2 \times 10^{-6}\,\mathrm{s} \tag{33}$$

The muon possesses one electronic charge and a mass 207 times that of an electron. It can enter into a Bohr orbit around an atom and thus form a muonic atom, Fig. 9, which, because of the orbit being reduced by a factor of 207, makes it look like an "oversize" neutron to another ion. This feature is of paramount significance because another hydrogen ion may therefore approach this muonic atom sufficiently close for quantum mechanical tunnelling becoming a dominant mechanism for the formation of a compound nuclear state followed by fusion. We may therefore suggest a simple muon-catalysed D + T fusion process by



(34)

This representation emphasizes two further important considerations. First, the muon may, following DTμ fusion, attach itself to the alpha reaction product and thus be lost from any further catalytic action. Secondly, since the average energy cost of one muon is some 3000 MeV and each DTμ fusion releases only 17.6 MeV, the same muon would need to catalyse several hundred D + T fusion reactions; therefore, since the muon mean life is only 2.2×10^{-6} s and is unaffected by whether it is bound in a Bohr orbit or is free, the various reaction stages need to proceed at rates considerably faster than 10^{8} s^{-1}.

We add the comment here that should the D-T-μ process by itself not be energetically viable, then the fusion neutron produced in this reaction could need to be multiplied in a blanket surrounding the D-T-μ reaction chamber and then used for fissile fuel breeding purposes; the ensuing 200 MeV fission energy released per bred fissile nucleus could, in principle become dominant in the energy balance analysis of such an accelerator-fusion-fission "tribid" system.

Further thought suggests that Eq. (33) represents an incomplete representation of the muon-catalysed process. We depict a more complete characterization of the various processes in Fig. 10. We have undertaken a kinetic and energetic analysis of this D-T-μ process described as follows.

We envisaged a chamber at close to room temperature containing an even mixture of D_2 and T_2 into which a pulse of muons is injected. Mass balance consideration then yields a system of rate equations of the type

$$\frac{dN_k}{dt} = -\lambda_\mu N_k + \sum_l \lambda_l N_l \pm \sum_{ij}\sum p_{ij} K_{ij} N_i N_j \qquad K = 1,2,.... \tag{35}$$

where N_i and N_j are the densities of the various muonic species, λ_j is the decay constant of N_j, p_{ij} are the several reaction channel probabilities and K_{ij} are used as defined in Eq. (7).

The nuclear power produced as a function of time is given by

$$P(t) = \sum_{ij}\sum K_{ij} N_i N_j Q_{ij} + \sum_k \lambda_k N_k Q_k \tag{36}$$

where Q_{ij} is the energy released in the time dependent fusion rate involving N_i and N_j, and Q_k is the decay energy; thus, the system of Eq. (35) needs to be solved for all N_i and N_j as a function of time.

Finally, the Q-value of the reaction scheme, defined as "energy-out over energy-in" for the duration of this pulse, is given by

$$Q = \frac{\int_0^\infty P(t)dt}{N_\mu^\circ E_\mu} \tag{37}$$

where N_μ° is the muon density initially injected and E_μ is its average energy cost.

Using the data largely based on USSR sources - which involves the linearization of Eq. (35) as

$$\frac{dN_k}{dt} = \pm \sum_i p_{ik}\lambda_{ik}N_k \qquad k = 1,2,... \tag{38}$$

with λ_{ik} either measured experimentally for the D_2 - T_2 mixture of interest or determined from theoretical considerations, we have evaluated the above system and display a typical particle density and power history in Fig. 11.

Introducing some variations in the more uncertain λ_{ij} constants suggests that the Q-value is likely to be around 0.3; the number of catalyzed cycles one muon may generate seems to be between 50 and 100.

This preliminary analysis indicates that use of the fusion produced neutron may need to be made by coupling the D+T+μ processes to a n+Fi process.

V. EMERGING CONNECTIONS

Several aspects of the preceeding analysis hold promise of some interesting and potentially very relevant consequences. We consider some of these possibilities next.

V.1 Fusion Chains and Nucleokinetics

The fusion chain kinetics expression, Eq. (27), provides an interesting connection to several other currently topical fields.

The relation of Eq. (27) to fission physics occurs at two points of reference. First, unlike fission chains which involve the multiplication of the chain carrier in a given reaction, the fusion chain is characterized by partial carrier regeneration and hence demands the existance of coupled reactions. Second, a squared density term - which accounts for the asymptotic behaviour of the fusion chain - does not appear in fission reactor physics because the neutron-neutron capture cross section is totally negligible; it is fascinating to speculate on the direction fission physics and nuclear morphogenesis would have taken if this were otherwise.

The evident appearance of fusion chains according to the line of reasoning indicated here may suggest that certain chain carriers may play a role in stellar nucleoexplosive processes. That is, the substantial bursts of energy which accompany processes such as a supernova might be fusion chains under conditions for which the coefficients, a_i of Eq. (27), are appropriate.

As a final point we comment on a possible connection with fusion chains and the Feigenbaum constant λ_c. We rewrite the fusion chain kinetics equation, Eq. (27), without carrier subsidization in the form

$$\frac{dN_c}{dt} = a_1N_c - a_2N_c^2 \tag{39}$$

and define

$$X = \frac{a_2}{a_1} N_c \tag{40}$$

to obtain Eq. (39) in the form

$$\frac{dX}{dt} = a_1 X(1 - X) \tag{41}$$

This equation has been shown by Feigenbaum to exhibit some interesting properties. For example, for

$$a_1 < \lambda_c = 3.5699 \; .... \tag{42}$$

the function displays periodic behaviour and chaotic for

$$a_1 > \lambda_c \tag{43}$$

The interesting question here is that the coefficients a_1 and a_2 are defined in terms of physical properties such as nuclear cross sections and particle energies and depend upon the chosen reaction cycle and the fusing conditions. It is, therefore, tempting to view $a_1 = \lambda_c$ as a kind of bifurcation parameter which may relate to the state of fusion supercritically. Further research is evidently required to explore these implications.

V.2 Reaction Synergism and Nonlinear Kinetics

The particle density rate expression for the muon-catalytic processes, Eq. (35), may be generalized to any population characterized by destruction/creation processes. Such a generalization is given by

$$\frac{dN_k}{dt} = S_k - \lambda_k N_k + \sum_l \lambda_l N_l \pm \sum_{ij}\sum p_{ij} K_{ij} N_i N_j \tag{44}$$

where S_k refers to the external subsidization of N_k, $\lambda_k N_k$ identifies radioactive decay, $\lambda_l N_l$ represents the production rate of N_k from decaying precursers and the last term refers to collisional creation-destruction of N_k as well as self-fusion (for $i = j = k$).

As a particular low order characterization we take k = 1 and 2, assume *no* subsidization, and no self-fusion to obtain

$$\begin{aligned} \dot{N}_1 &= \pm\, a_1 N_1 - a_2 N_1 N_2 \\ \dot{N}_2 &= \pm\, b_1 N_2 - b_2 N_1 N_2 \end{aligned} \tag{45}$$

Except for the signs, this set of coupled equations possesses the same form as the pioneer predator-prey equations of Lotka-Volterra. Such an analogy is, in a sense, expected because the nuclear particles are born and then destroyed by interaction. If binary self-destruction were to occur then N_i^2 terms would also appear.

An indication of the interesting reaction kinetics formulation quite analogous to nonlinear dynamics analysis becomes apparent from an examination of slightly more complex reaction couplings. For example, the system of Chain B, Fig. 5, can be shown to be represented by

$$\dot{X} = a_0 - a_1XY + a_2YZ + a_3Z^2 \tag{46a}$$

$$\dot{Y} = b_0 - b_1XY - b_2YZ \tag{46b}$$

$$\dot{Z} = c_0 + c_1XY - c_2YZ - c_3Z^2 \tag{46c}$$

where X,Y, and Z are the proton densities, the ^6Li densities, and the ^3He densities, respectively; the constants a_0, b_0 and c_0 are subsidization rates of X, Y, and Z; the remaining parameters are the effective reaction reactivity parameters.

It is tantalizing to explore the kinetic characteristics of a set such as Eq. (45) particularly from the point of view of identifying any domain of "attractors". Note, however, that in practice the various coefficients may be operational variables and hence the mathematical properties of a system of equations become related to system design and operational features.

V.3 Parent-Satellite Systems

As a final extension we consider the concept of a Parent-Satellite nuclear energy systems concept. If the accelerator-fusion interface is well established then one may consider a central deuterium fuelled parent fusion reactor operating on in the semicatalyzed (SCAT-D) mode. As suggested in Fig. 12, the bred tritium is consumed at its rate of production and the bred ^3He is extracted as fuel feed-stock for many small fusion reactors optimized for the D - ^3He cycle

$$D + {}^{3}He \rightarrow \alpha + p \qquad (47)$$

Since only charged particles appear in the primary reaction, the process is radiologically very "clean" and, additionally, efficient if direct energy conversion of the charged particles is employed. Their use as electricity producers in individual buildings - hospitals, appartment buildings and other institutions - will render their function equivalent to nuclear large batteries in the 1 to 2 MW_e range.

An interesting byproduct may be the use of the fusion neutrons as breeders of fissile fuel for an external fission economy or to view the core-blanket assembly as a fusion-hybrid reactor.

V CONCLUSION

The synergism of the light elements directed to attainable systems for the delivery of acceptable forms of nuclear energy is characterized by two contrasting properties: challenge and uncertainty.

The challenge to contribute to the definition and direction of a strategy based on substantial alternative approaches is substantial. The uncertainty is the price to be paid and the risks to be taken in the continuing search for knowledge and understanding of natural processes. But then, these features have always marked the life of scientists-technologists and the existance of research-development institutes.

At the more immediate level of emphasis, the investments appear principally in time and intellectual efforts. It is subsequently that major decisions need to be made.

For the near term, therefore, the synergism of the light elements is worthy of intense exploration.

BIBLIOGRAPHY

This bibliography has been assembled to be indicative, rather than exhaustive, of the subjects discussed. The entries are listed alphabetically and grouped in two parts.

Journal Articles

1. V.M. Bystritsky, et al., JETP Lett (Engl. Transl.) 31, 229 (1980)

2. M. Feigenbaum, LASL Report (1981)

3. S.S. Gershtein, et al., Sov. Phys. JETP (Engl. Transl.) 51, 1053 (1980)

4. A.A. Harms and W. Haefele, American Scientist, 69, 310 (1981)

5. A.A. Harms and M. Heindler, Acta Physica Austriaca, 52, 301 (1980)

6. A.A. Harms and E.M. Krenciglowa, Nuclear Fusion, 20, 665 (1980)

7. A.A. Harms and S.G. Lie, Transactions of the American Nuclear Society, 39, 240 (1981)

8. S.G. Lie and A.A. Harms, Nuclear Science and Engineering, 80, 124 (1982)

9. J.R. McNally, Nuclear Fusion, 11, 187 (1971), also 18, 133 (1978)

10. G.H. Miley, Atomkernenergie, 32, 12 (1978)

11. Y.V. Petrov, Nature, 285, 466 (1980)

12. K.F. Schoepf and A.A. Harms, Transactions of the American Nuclear Society, 38, 537 (1981)

13. K.F. Schoepf, et al., Journal of Fusion Energy, 2, 181 (1982)

14. G.W. Shuy and R.W. Conn, Transactions of the American Nuclear Society, 33, 101 (1979)

Books

1. C.K. Choi, Ed., Proc. Review Mtg. Advanced Fuel Fusion, EPRI-ER-536-SR, (1979)

2. H. Haken, Ed. (Various conference books on synergism), Springer Verlag

3. A.A. Harms and M. Heindler, Nuclear Energy Synergetic, Plenum Publ. Co. (1982)

4. B.C. Maglich, Ed., Proc. First Symposium on Clean Energy, Nuclear Instrument and Methods, 144 (1977)

5. G. Nicolis and I. Prigogine, Self-Organization in Nonequilibrium Systems, Wiley (1977)

Table I: Advanced Fusion Reactions

#	Reaction			Q-value (MeV)	(ion/neutron) ratio
1	D + T	→	n + α	17.6	1/1
2	D + D	→	T + p	4.0	2/0
			^{3}H + n	3.3	1/1
3	D + ^{3}He	→	α + p	18.3	2/0
4	D + ^{6}Li	→	^{7}Be + n	3.4	1/1
			^{7}Li + p	5.0	1/0
			p + α + T	2.0	3/0
			2α	22.3	2/0
			^{3}He + α + n	1.8	2/1
5	D + ^{7}Li	→	n + 2α	15.1	2/1
6	D + ^{7}Be	→	p + 2α	16.8	3/0
7	T + T	→	α + 2n	11.3	1/2
8	T + ^{3}He	→	D + α	14.3	2/0
			p + α + n	12.1	2/1
9	^{3}He + ^{3}He	→	2p + α	12.8	3/0
10	^{3}He + ^{6}Li	→	2α + p	16.9	3/0
			^{7}Be + D	0.1	2/0
11	^{3}He + ^{7}Li	→	2α + 2p	9.6	4/0
12	^{3}He + ^{9}Be	→	3α	20.0	3/0
13	p + ^{6}Li	→	α + ^{3}He	4.0	2/0
14	p + ^{7}Li	→	2α	17.4	2/0
15	p + ^{9}Be	→	D + 2α	0.7	3/0
			^{6}Li + α	2.1	2/0
16	p + ^{11}B	→	3α	8.7	3/0
17	α + ^{6}Li	→	p + ^{9}Be		2/0

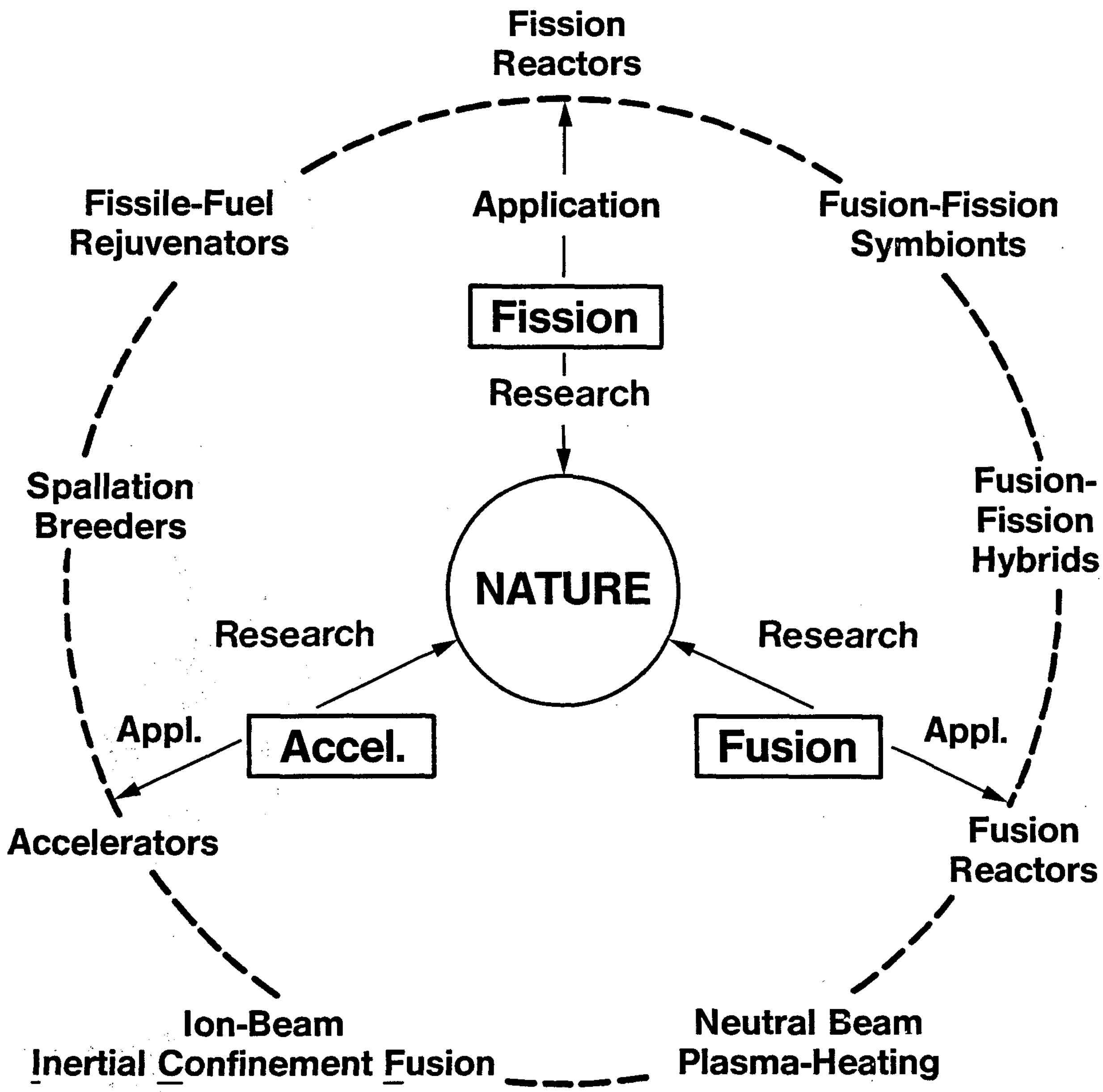


Fig. 1: Schematic depiction of the symbiosis involving the three primary process-technologies of fission, fusion and acceleration.

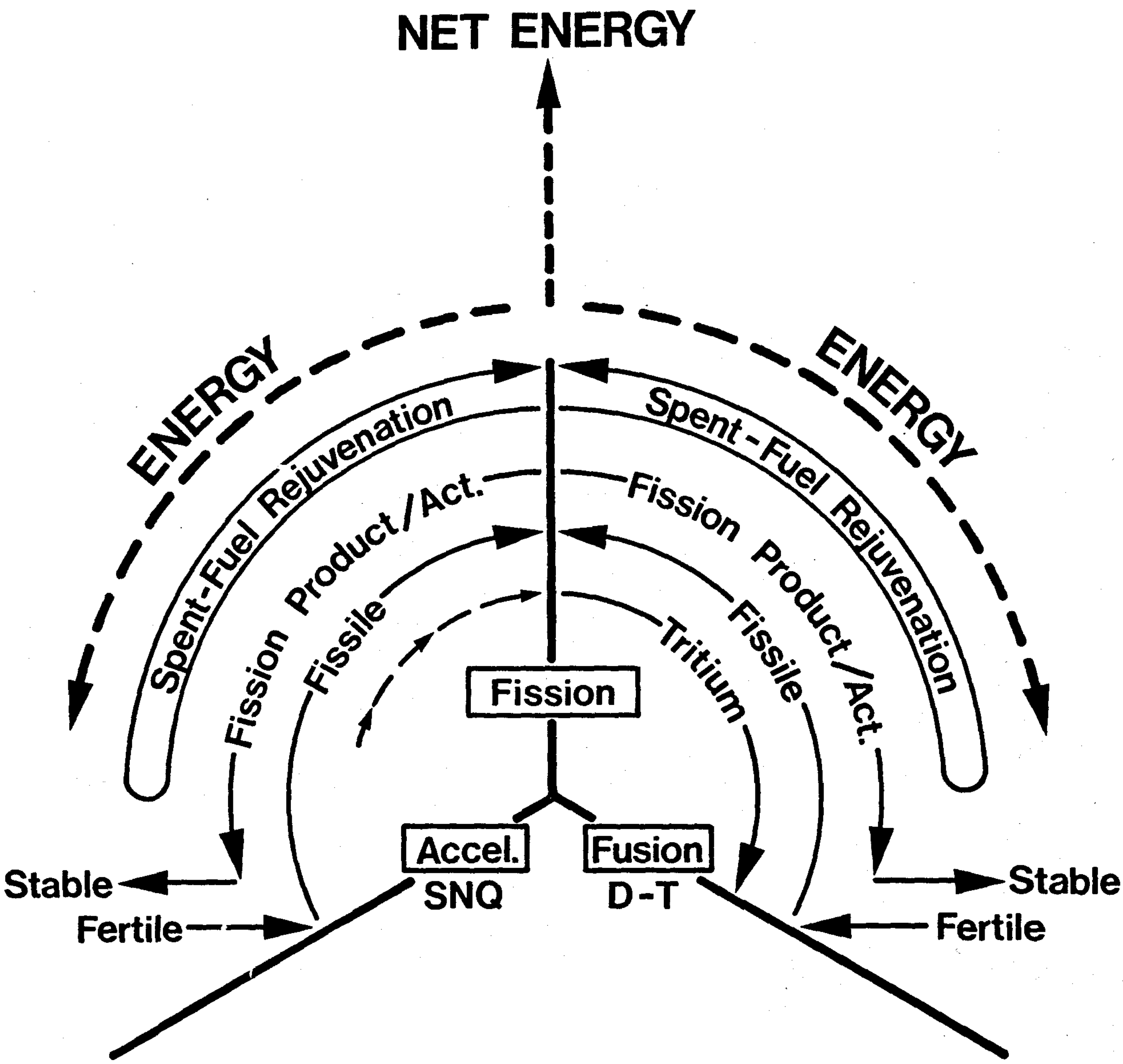


Fig. 2: Identification of mass and energy flows for the fission-acceleration and fission-fusion interface domains.

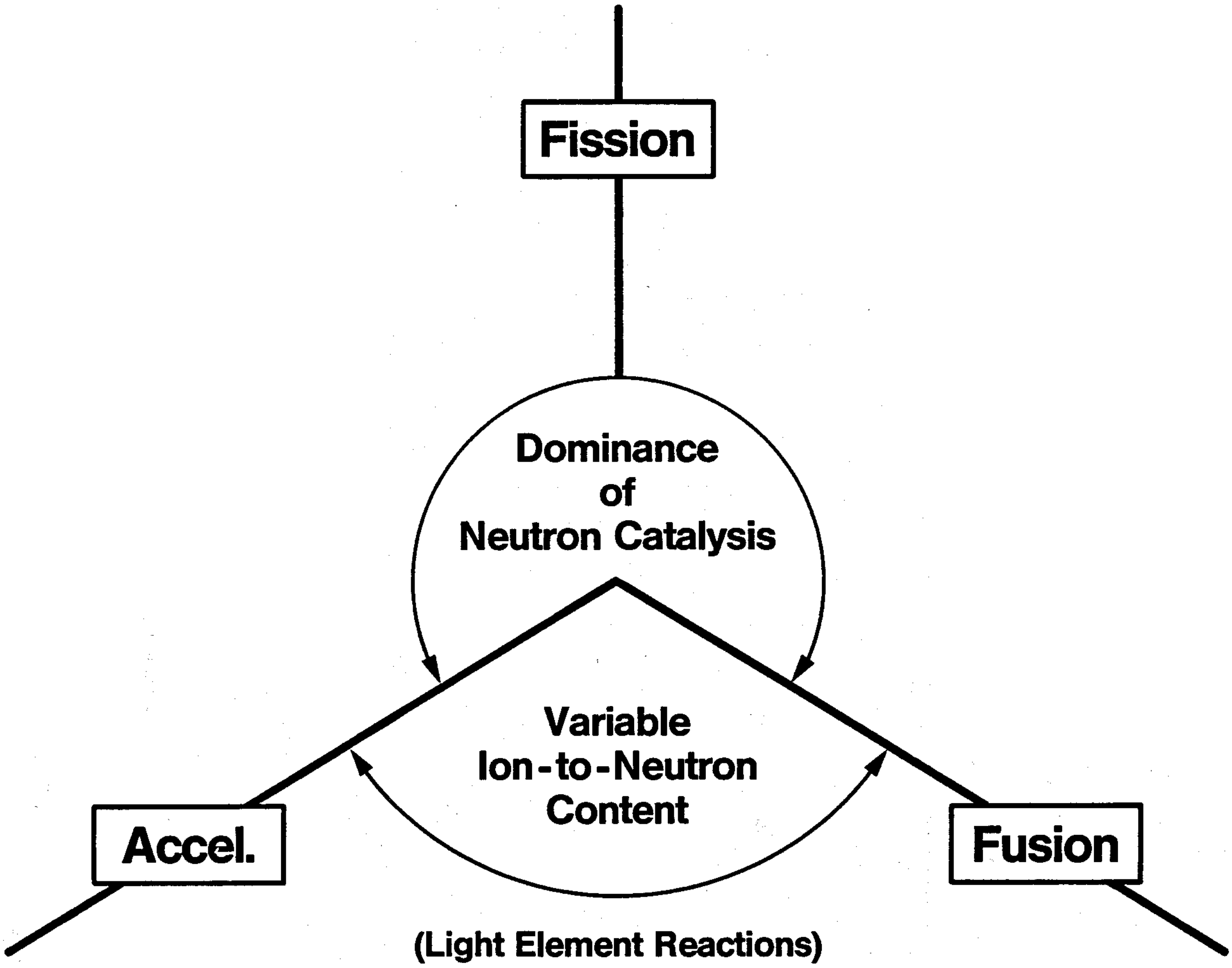


Fig. 3: Depiction of the underlying physical processes which distinguish the interactive domains involving the primary phenomena of fission, fusion and acceleration.

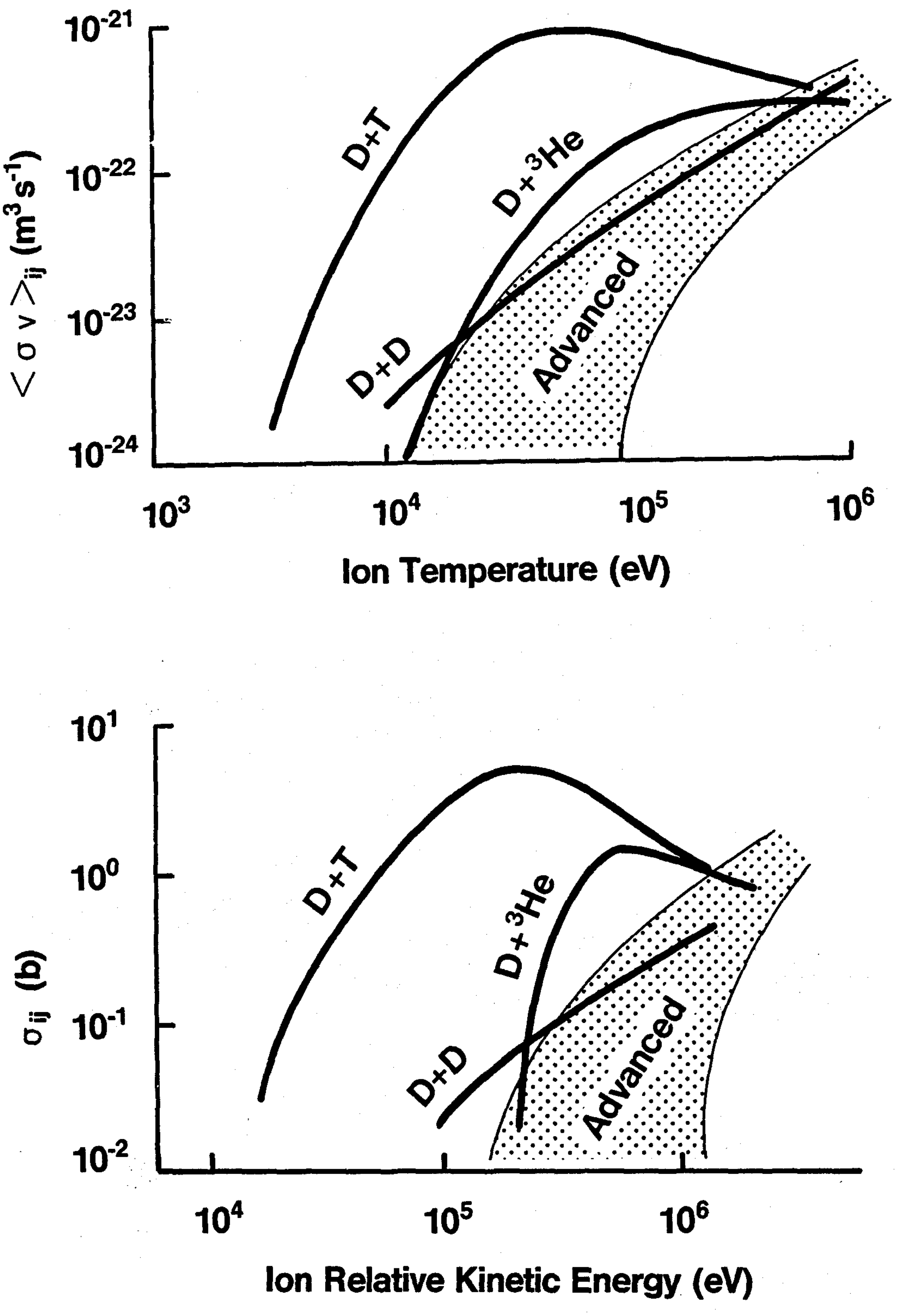


Fig. 4: Approximate representations of the cross section and reactivity variations for fusion reactions.

Chain A

$$D + {}^{6}Li \longrightarrow \{\alpha + T + p\}$$

$$^{6}Li + T \longrightarrow \{D + {}^{7}Li\}$$

$$^{6}Li + p \longrightarrow {}^{3}He + \alpha$$

$$^{6}Li + {}^{3}He \longrightarrow \{D + {}^{7}Be\}$$

Chain B

$$p + {}^{6}Li \longrightarrow {}^{3}He + \alpha$$

$$^{6}Li + {}^{3}He \longrightarrow \{p + 2\alpha\}$$

$$^{3}He + {}^{3}He \longrightarrow \alpha + 2p$$

Fig. 5: Listing of two fusion chains.

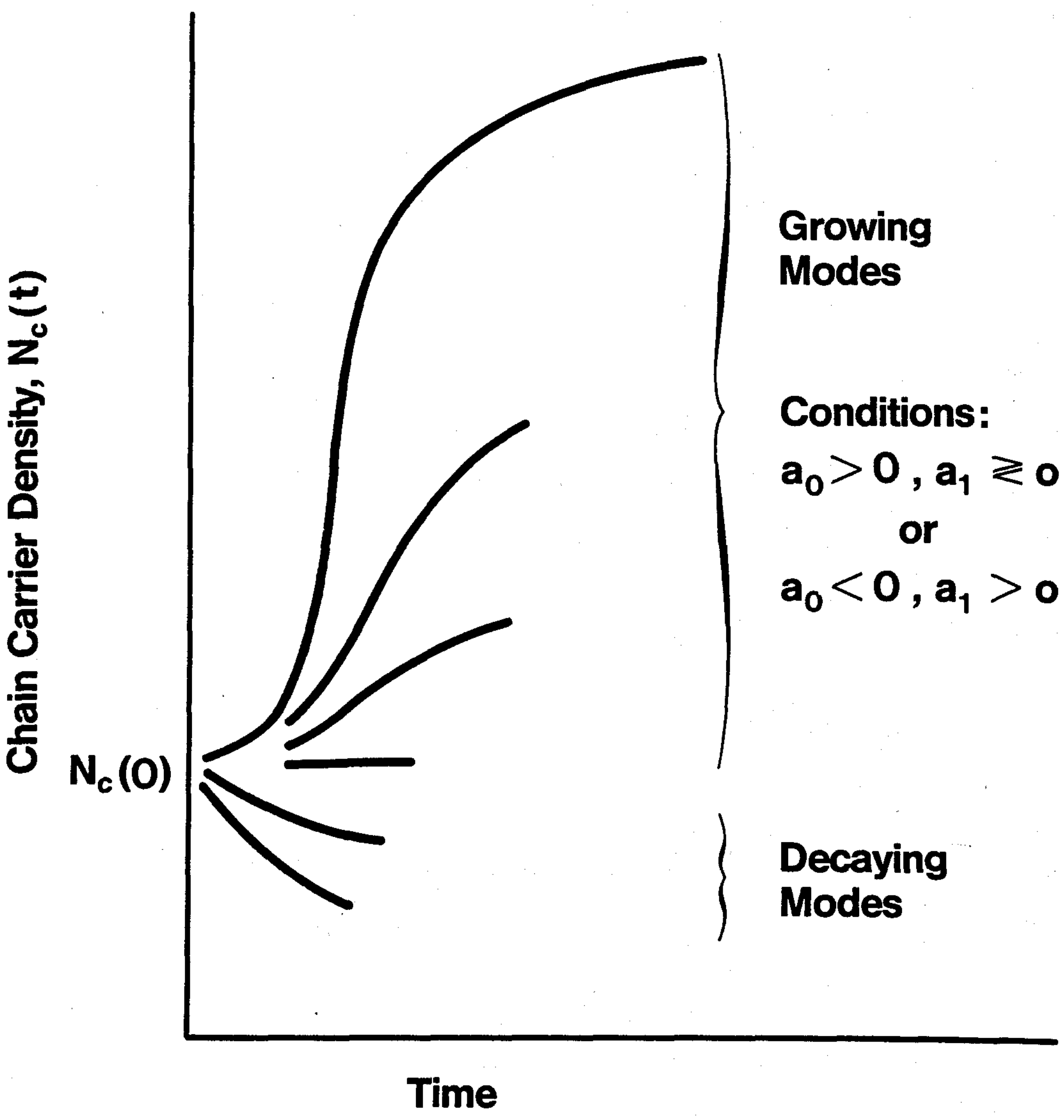
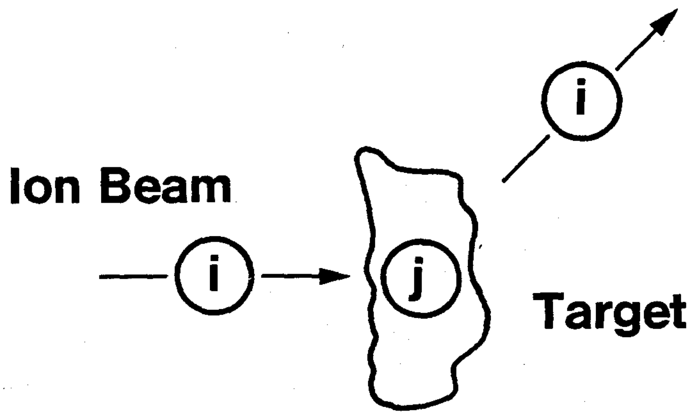
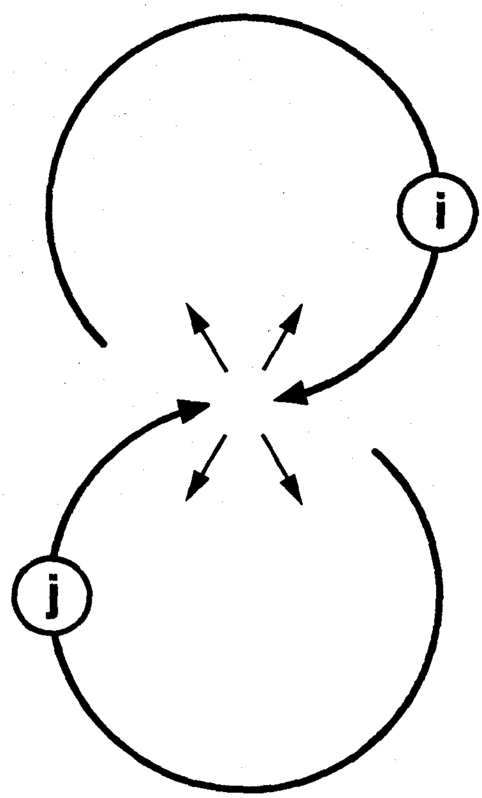


Fig. 6: Illustration of the distinguishing kinetic features of the fusion chain carrier density as a function of time.



a) Beam-Target Interaction



b) Colliding-beam Interaction

Fig. 7: Depiction of beam-target and colliding-beam interactions

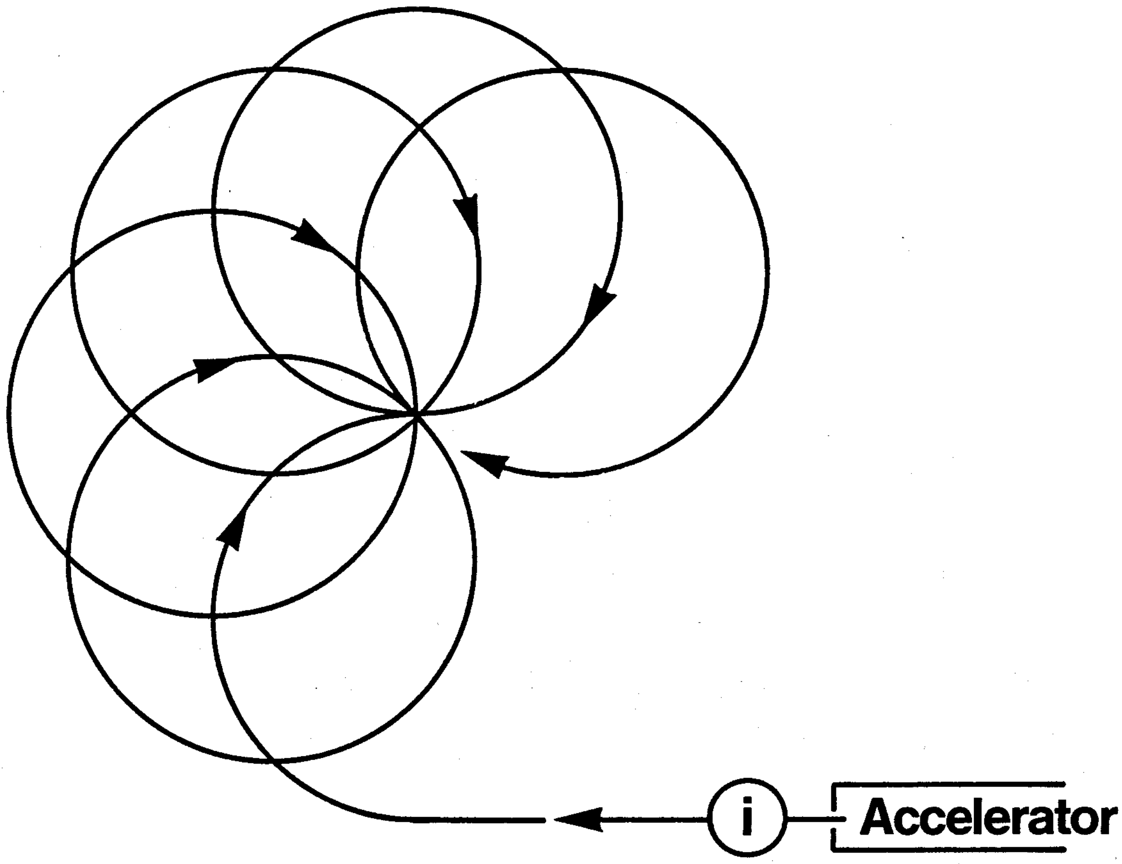


Fig. 8: Schematic of the redirected-beam approach to fusion. Here, a magnetic field, vertical to this plane, redirects the ion trajectories towards the high density center.

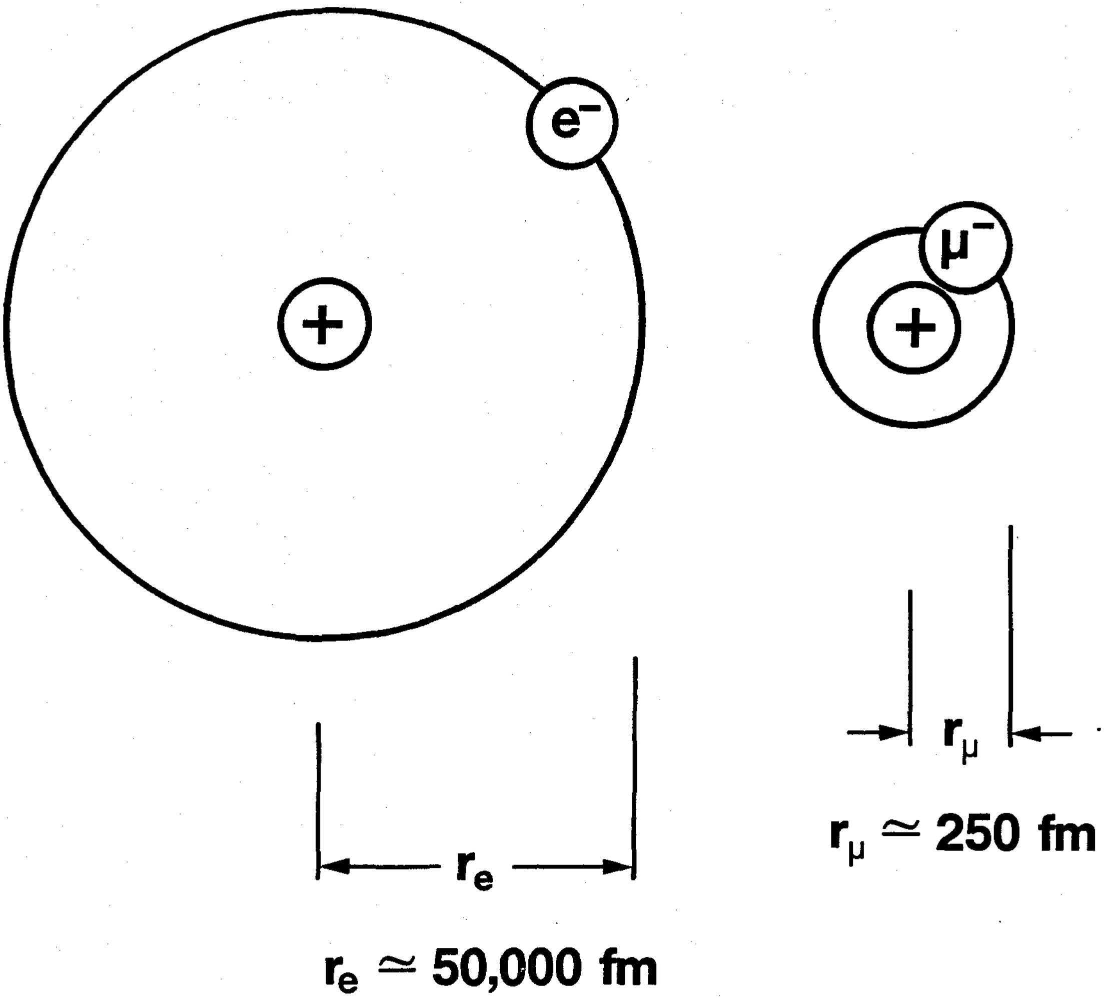


Fig. 9: Dimensional depiction of a conventional hydrogen atom and a muonic atom (not to scale).

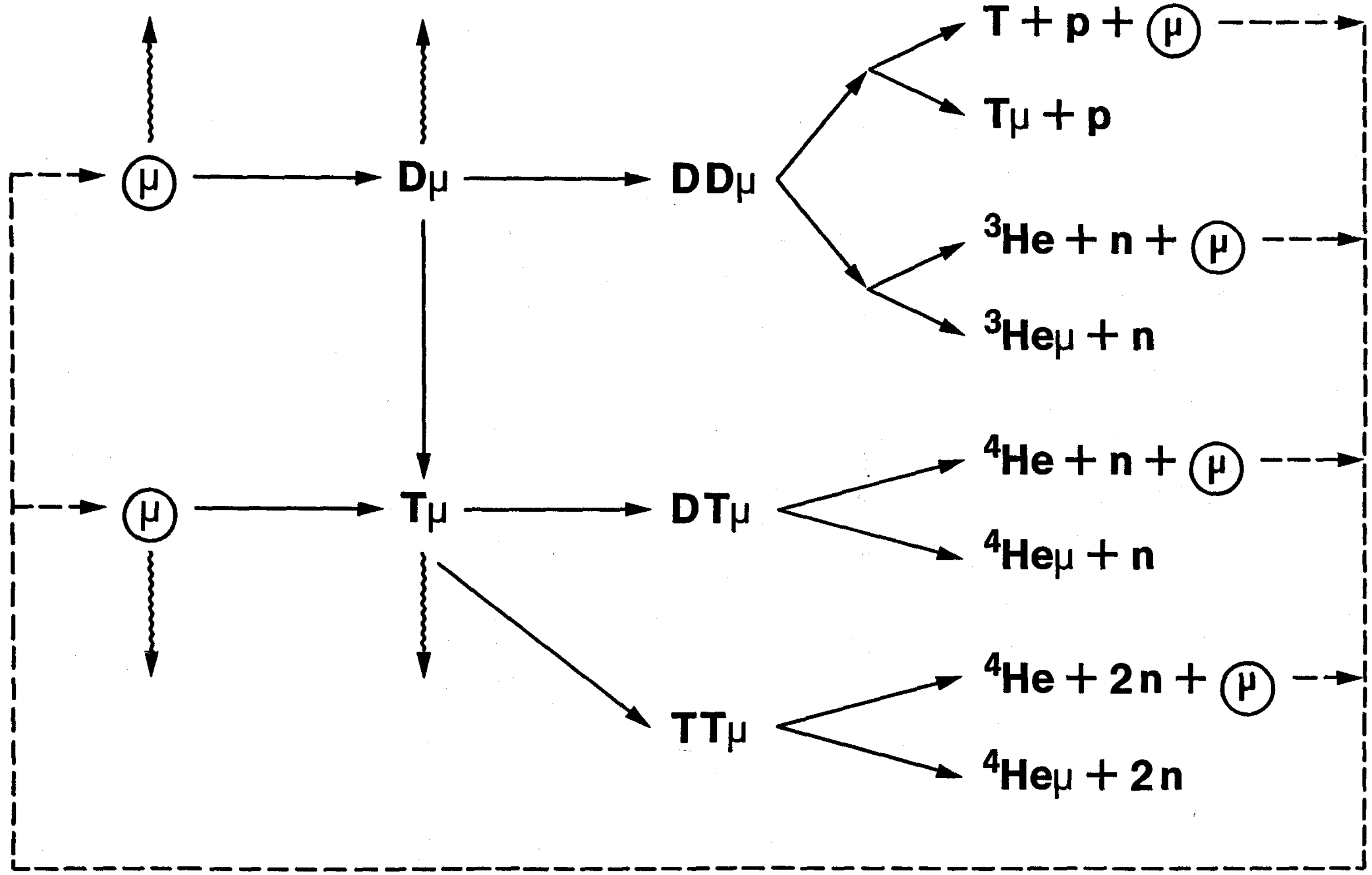


Fig. 10: Reaction schema of the D-T-μ fusion process

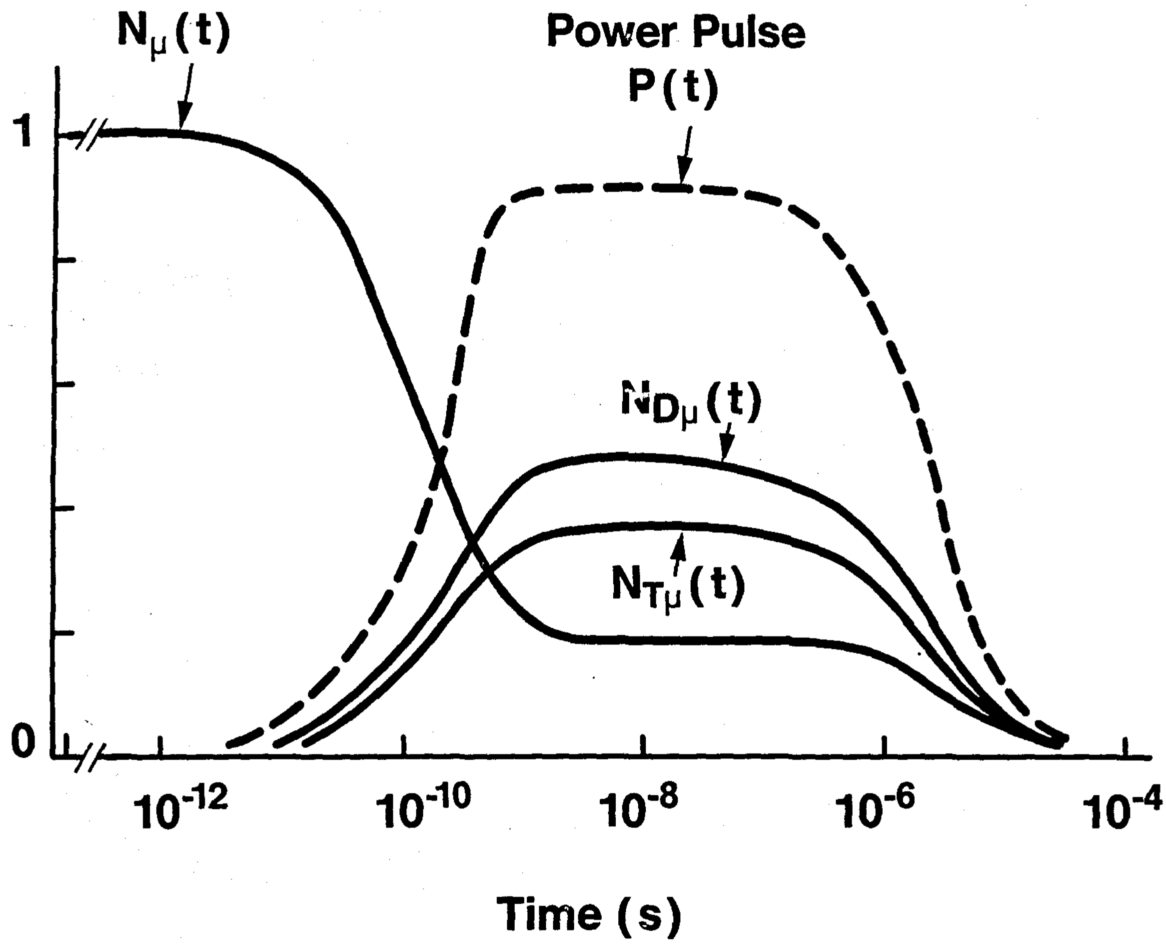


Fig. 11: Time dependencies of the muon-induced fusion power pulse and selected muonic particle densities

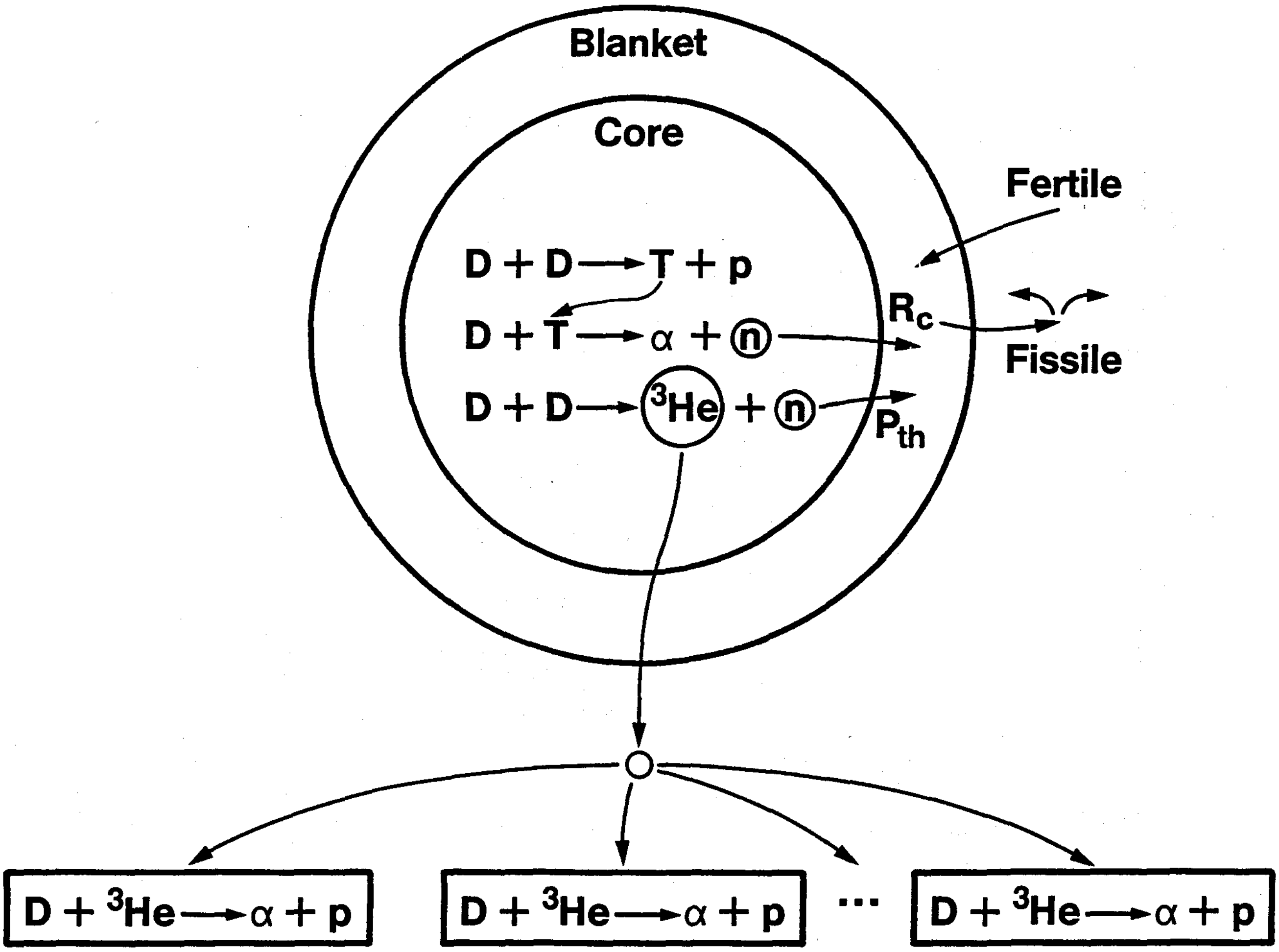


Fig. 12: Schematic of SCAT-D parent fusion reaction supplying ^3He fuel for numerous small D-^3He burning direct energy conversion fusion devices